AD

AD 733906

Research and Development Technical Report
ECOM-3482

BULK SEMICONDUCTOR QUASI-OPTICAL CONCEPT FOR GUIDED WAVES FOR ADVANCED MILLIMETER WAVE DEVICES

Metro M. Chrepta
Harold Jacobs

September 1971

DISTRIBUTION STATEMENT
Approved for public release;
distribution unlimited.

ECOM

UNITED STATES ARMY ELECTRONICS COMMAND · FORT MONMOUTH, N.J.

39

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) U. S. Army Electronics Command, Fort Monmouth, New Jersey 07703	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED
	2b. GROUP

3. REPORT TITLE
BULK SEMICONDUCTOR QUASI-OPTICAL CONCEPT FOR GUIDED WAVES FOR ADVANCED MILLIMETER WAVE DEVICES.

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Technical Report

5. AUTHOR(S) (First name, middle initial, last name)
Metro M. Chrepta and Harold Jacobs

6. REPORT DATE September 1971	7a. TOTAL NO. OF PAGES 33	7b. NO. OF REFS 4

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S) ECOM-3482
b. PROJECT NO. 1S6-[illegible]705-A-056	
c. Task No. -04	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d. Work Unit No. -44	

10. DISTRIBUTION STATEMENT
This document has been approved for public release and sale; its distribution is unlimited

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY U. S. Army Electronics Command ATTN: AMSEL-TL-SA Fort Monmouth, New Jersey 07703

13. ABSTRACT

Recent suggestions have been made for the design of bulk semiconductor millimeter wave devices, and in particular, a new type of phase shifter. In order for these designs to perform in a satisfactory manner it was found necessary to demonstrate that electromagnetic propagation would occur largely in the interior of a semiconductor dielectric waveguide with relatively low loss. In this report an analysis is made of electromagnetic waves guided in an infinite slab of material with the properties of high resistivity silicon. Calculations and preliminary experiments are demonstrated at frequencies near 10.0 GHz. It is concluded that propagation in the semiconductor medium offers the possibility of low loss circuitry and satisfies the requisites for device design.

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

Security Classification

NOTICES

Disclaimers

The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

The citation of trade names and names of manufacturers in this report is not to be construed as official Government indorsement or approval of commercial products or services referenced herein.

Disposition

Destroy this report when it is no longer needed. Do not return it to the originator.

UNCLASSIFIED

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Dielectric Waveguides						
Millimeter Waves in Silicon						
Bulk Semiconductors						
Millimeter Wave Component						
Rectangular Dielectric Guides						
Slab Waveguides						
TM Wave Light Lines						
Semiconductor Components						

UNCLASSIFIED

Security Classification

Report Control Symbol
(RCS)OSD-1366

RESEARCH AND DEVELOPMENT TECHNICAL REPORT
ECOM-3482

BULK SEMICONDUCTOR QUASI-OPTICAL CONCEPT FOR GUIDED WAVES FOR ADVANCED MILLIMETER WAVE DEVICES

by

Metro M. Chrepta
Harold Jacobs

Semiconductor & Frequency Control Devices Technical Area
Electronics Technology and Devices Laboratory

September 1971

DA Work Unit No. 1S6-62705-A-056-04-44

Distribution Statement

This document has been approved for public release and sale; its distribution is unlimited.

U. S. ARMY ELECTRONICS COMMAND
FORT MONMOUTH, NEW JERSEY

CONTENTS

FIGURES

TABLES

ABSTRACT

Recent suggestions have been made for the design of bulk semiconductor millimeter wave devices, and in particular, a new type of phase shifter. In order for these designs to perform in a satisfactory manner it was found necessary to demonstrate that electromagnetic propagation would occur largely in the interior of a semiconductor dielectric waveguide with relatively low loss. In this report an analysis is made of electromagnetic waves guided in an infinite slab of material with the properties of high resistivity silicon. Calculations and preliminary experiments are demonstrated at frequencies near 16.0 GHz. It is concluded that propagation in the semiconductor medium offers the possibility of low loss circuitry and satisfies the requisites for device design.

APPENDICES

BLANK PAGE

BULK SEMICONDUCTOR QUASI-OPTICAL CONCEPT FOR GUIDED WAVES
FOR ADVANCED MILLIMETER WAVE DEVICES

INTRODUCTION

In a recent proposal[1] we have suggested the design of bulk semiconductor devices and the use of semiconductor waveguides to replace more conventional stripline and metal waveguides for the millimeter wave regions of the spectrum.

It is well known that metallic waveguides become lossy at shorter wavelengths (1 dB per foot at 3.2 mm or 1.5 dB per foot at 2.15 mm). The use of dielectric guides offers a promise of lower losses as the wavelengths approach the optical regions. With the advent of recently obtainable high resistivity silicon, low loss semiconductors offer an attractive potential as a guide material. The additional factor here is that components and devices could conceivably be "built in" the semiconductor line so that in effect one would have an optical line with active elements incorporated. The first considerations involved in evaluating such a concept is the direct test of a single straight section of semiconductor dielectric guide to determine the losses which might result. A factor in this line of thought is that if the energy flow is almost entirely within the waveguide, it would be relatively easy to control by electrical means. If the energy flow is along the direction of the guide but contained in the air space surrounding the semiconductor guide it would be relatively difficult to control. See Figure 1.

The first consideration is to estimate the chances of power flow within the guide material, where it can be modulated, amplified, detected, etc., by devices constructed and located within the semiconductor structure. In what follows we shall describe first some analytical considerations of the semiconductor system relying on the wave guided in a dielectric slab. This will then be followed by some initial experiments designed to prove that almost all of the energy is contained in the semiconductor.

DIELECTRIC SLAB WAVEGUIDE

We consider a dielectric slab oriented in the indicated position in Figure 2. Here we assume an infinite dielectric slab with no variations of field in the x direction.

The general form of Maxwell's Equations are[2]:

$$\left.\begin{array}{ll}
\dfrac{\partial H_z}{\partial y} - \dfrac{\partial H_y}{\partial z} = j\omega\epsilon E_x & \dfrac{\partial E_z}{\partial y} - \dfrac{\partial E_y}{\partial z} = -j\omega\mu H_x \\[2ex]
\dfrac{\partial H_x}{\partial z} - \dfrac{\partial H_z}{\partial x} = j\omega\epsilon E_y & \dfrac{\partial E_x}{\partial z} - \dfrac{\partial E_z}{\partial x} = -j\omega\mu H_y \\[2ex]
\dfrac{\partial H_y}{\partial x} - \dfrac{\partial H_x}{\partial y} = j\omega\epsilon E_z & \dfrac{\partial E_y}{\partial x} - \dfrac{\partial E_x}{\partial y} = -j\omega\mu H_z
\end{array}\right\} \quad (1)$$

$$\left.\begin{aligned}\frac{\partial^2 \bar{E}}{\partial x^2} + \frac{\partial^2 \bar{E}}{\partial y^2} + \frac{\partial^2 \bar{E}}{\partial z^2} &= -\omega^2\mu\epsilon \bar{E} \\ \frac{\partial^2 \bar{H}}{\partial x^2} + \frac{\partial^2 \bar{H}}{\partial y^2} + \frac{\partial^2 \bar{H}}{\partial z^2} &= -\omega^2\mu\epsilon \bar{H}\end{aligned}\right\} \quad (2)$$

Propagation is in the z direction so that we use the form

$$e^{-\bar{\gamma} z}, \qquad \bar{\gamma} = \bar{\alpha} + j\bar{\beta}.$$

Furthermore $\bar{E}$ and $\bar{H}$ can be a function of y but cannot be a function of x, bu assumption. This means that all terms with $\frac{\partial}{\partial x} = 0$, and $\frac{\partial}{\partial z}$ is replaced by $-\bar{\gamma}$.

We next take this into account in (1).

$$\left.\begin{aligned} \frac{\partial H_z}{\partial y} + \bar{\gamma} H_y &= j\omega\epsilon E_x & \qquad \frac{\partial E_z}{\partial y} + \bar{\gamma} E_y &= -j\omega\mu H_x \\ -\bar{\gamma} H_x &= j\omega\epsilon E_y & -\bar{\gamma} E_x &= -j\omega\mu H_y \\ -\frac{\partial H_x}{\partial y} &= j\omega\epsilon E_z & +\frac{\partial E_x}{\partial y} &= +j\omega\mu H_z \end{aligned}\right\} \quad (3A)$$

These equations can now lead us into the calculations of either TM or TE modes. We choose the former to illustrate physical principles.

The TM mode:

$$\left.\begin{aligned} H_x &= H_x^0 e^{-\bar\gamma z}, \quad H_y = H_y^0 e^{-\bar\gamma z}, \quad H_z = 0 \\ E_x &= E_x^0 e^{-\bar\gamma z}, \quad E_y = E_y^0 e^{-\bar\gamma z}, \quad E_z = E_z^0 e^{-\bar\gamma z} \end{aligned}\right\} (3B)$$

We also require

$$\left.\begin{aligned} \nabla^2 E_x^0 &= -\omega^2 \mu\epsilon E_x^0 \\ \frac{\partial^2 E_x^0}{\partial y^2} + \gamma^2 E_x^0 &= -\omega^2\mu\epsilon E_x^0 \\ \frac{\partial^2 E_x^0}{\partial y^2} &= E_x^0(-\gamma - \omega^2\mu\epsilon) \end{aligned}\right\} (3C)$$

Next we consider the fields outside the dielectric slab, $y > a/2$ and inside the dielectric slab $y < a/2$.

First consider the fields <u>outside</u> the slab, $y > a/2$

$$H_x = H_x^0 e^{-\gamma_0 z}, \qquad (4)$$

by $\nabla^2 H_x = -\omega^2\mu\epsilon H_x$

$$\frac{\partial^2 H_x}{\partial y^2} + \gamma_0^2 H_x = -\omega^2\mu\epsilon H_x \qquad (5)$$

$$\frac{\partial^2 H_x}{\partial y^2} = -(\gamma_0^2 + \omega^2 \mu \epsilon) H_x = h_0^2 H_x \qquad (6)$$

where $h_0^2 = -\gamma_0^2 - \omega^2 \mu \epsilon$.

Next, $H_x^0 = C e^{-h_0 y}$, (7)

by (3A) $\gamma_0 H_x = -j \omega \epsilon E_y$

$$E_y^0 = \frac{j \gamma_0}{\omega \epsilon_v} H_x^0, \qquad (8)$$

by (3B) $E_z^0 = \frac{j}{\omega \epsilon_v} \frac{\partial H_x^0}{\partial y}$, but $\frac{\partial H_x^0}{\partial y} = -h_0 H_x^0$

$$E_z^0 = \frac{-j h_0}{\omega \epsilon_v} H_x^0 \qquad (9)$$

$$E_z^0 = -\frac{j h_0}{\omega \epsilon_v} C e^{-h_0 y}. \qquad (10)$$

Note we have the following terms as a function of H_x^o

$H_x^o = C e^{-h_0 y}$ $\qquad$ $h_0^2 = \gamma_0^2 - \omega^2 \mu \epsilon$

$E_y^o = \frac{j \gamma_0}{\omega \epsilon_v} H_x^o$ $\qquad$ E_y is $\perp$ to surface

$E_z^o = -\frac{j h_0}{\omega \epsilon_v} H_x^o$ $\qquad$ H_x is // to surface.

E_z is // to propogation direction

Power $= E_y \times H_x$

This is related to rectangular guide as in Figure 4.

Inside the slab; $\mu,\ \epsilon_1, \gamma_1\ ,\ y < a/2$

In the z direction of propagation

$$H_x = H_x^o e^{-\gamma_1 z}. \tag{11}$$

Note: $\gamma_1 = \gamma_0$ in order for fields to match across the surface.

Also by

$$\frac{\partial^2 H_x}{\partial y^2} + \gamma_1^2 H_x = -\omega^2 \mu \epsilon H_x \tag{12}$$

$$\frac{\partial^2 H_x^o}{\partial y^2} = -k_1^2 H_x^o \qquad k_1^2 = \gamma_1^2 + \omega^2 \mu \epsilon_1 \tag{13}$$

$$H_x^o = \sin k_1 y \quad \text{or} \quad H_x^o = \cos k_1 y. \tag{14}$$

These two cases are indicated as in Figure 5.

The surface impedance is

$$Z_s = -\frac{E_z}{H_x} = \frac{j h_0}{\omega \epsilon_v} . \qquad (15)$$

Since h_0 is real, Z_s is inductive reactive.

In summary we have the equations shown in Table I.

Table I: Equations for the TM Mode

Outside the Slab	Inside the Slab
$H_x = H_x^0 e^{-\gamma_0 z}$	$H_x = H_x^0 e^{-\gamma_1 z}$
$\frac{\partial^2 H_x^0}{\partial y^2} = h_0^2 H_x^0$	$\frac{\partial^2 H_x^0}{\partial y^2} = -k_1^2 H_x^0$
$h_0^2 = -\gamma_0^2 - \omega^2 \mu \epsilon_v$	$k_1^2 = \gamma_0^2 + \omega^2 \mu \epsilon_1$.
$H_x^0 = C e^{-h_0 y}$	$H_x^0 = \sin k_1 y$ and $\cos k_1 y$
$E_y^0 = \frac{j\gamma_0}{\omega \epsilon_v} H_x^0$	$E_y^0 = \frac{j\gamma_1}{\omega \epsilon_1} H_x^0$
$E_z^0 = \frac{j}{\omega \epsilon_v} \frac{\partial H_x^0}{\partial y}$	$E_z^0 = \frac{j}{\omega \epsilon_1} \frac{\partial H_x^0}{\partial y}$

$$E_z^c = \frac{j}{\omega \epsilon_1} \frac{\partial}{\partial y} \sin k_1 y = \frac{j k_1}{\omega \epsilon_1} \cos k_1 y$$

$$\text{or } E_z^0 = \frac{j}{\omega \epsilon_1} \frac{\partial}{\partial y} \cos k_1 y = -\frac{j k_1}{\omega \epsilon_1} \sin k_1 y$$

$$\gamma_1 = \gamma_0$$

Consider two possible modes of propagation.

Case I   For $-a/2 < y < a/2$, assuming $H_x^0 = \sin k_1 y$

$$H_x = Be^{-\gamma z} \sin k_1 y, \tag{16}$$

$$H_x = Ae^{-h_0 y}, \quad y > a/2 . \tag{17}$$

At the boundary, $y = a/2$

$$Ae^{-h_0 a/2} = B \sin(k_1 a/2). \tag{18}$$

Also at the boundary

$$E_{z_1} = E_{z_v} \quad \text{by (3A)}.$$

In general,

$$E_z = -\frac{1}{j\omega\epsilon_1} \frac{\partial H_x}{\partial y} \qquad H_x = Be^{-\gamma z} \sin k_1 y \tag{19}$$

$$E_{z_1} = -\frac{k_1}{j\omega\epsilon_1} Be^{\gamma z} \cos k_1 y, \quad -a/2 < y < a/2, \tag{20}$$

for $y > a/2$

$$E_{z_v} = -\frac{1}{j\omega\epsilon_v} \frac{\partial H_x}{\partial y}, \qquad H_x = Ae^{-h_0 y}, \tag{21}$$

$$E_{z_v} = \frac{h_0}{j\omega\epsilon_v} Ae^{-h_0 y}. \tag{22}$$

Hence at y = a/2,

$$\frac{h_0}{j\omega\epsilon_v} A e^{-h_0 a/2} = -\frac{k_1}{j\omega\epsilon_1} B \cos k_1 \frac{a}{2}. \qquad (23)$$

By (18) and (23),

$$\frac{h_0}{\epsilon_v} A e^{-h_0 a/2} = \frac{h_0}{\epsilon_v} B \sin\left(k_1 \frac{a}{2}\right)$$

$$\frac{h_0}{\epsilon_v} A e^{-h_0 a/2} = -\frac{k_1}{\epsilon_1} B \cos\left(k_1 \frac{a}{2}\right)$$

$$\frac{h_0}{\epsilon_v} \sin\left(k_1 \frac{a}{2}\right) = -\frac{k_1}{\epsilon_1} \cos\left(k_1 \frac{a}{2}\right)$$

$$\frac{\epsilon_1 h_0}{\epsilon_v k_1} = -\cot\left(k_1 \frac{a}{2}\right)$$

$$-\frac{\epsilon_v k_1}{\epsilon_1} \cot\left(k_1 \frac{a}{2}\right) = h_0. \qquad (24)$$

In addition:

$$h_0^2 = -\gamma_0^2 - \omega^2\mu\epsilon_v$$
$$k_1^2 = \gamma_1^2 + \omega^2\mu\epsilon_1$$ by definition, (25)

adding

$$h_0^2 + k_1^2 = \omega^2\mu(\epsilon_1 - \epsilon_v). \qquad (26)$$

Multiplying (24) by $a/2$, and (26) by $\left(a/2\right)^2$

$$-\frac{\epsilon_r k_1}{\epsilon_1}\frac{a}{2}\cot\left(k_1\frac{a}{2}\right) = h_0\frac{a}{2} \qquad (27)$$

$$\frac{h_0^2 a^2}{2^2} + \frac{k_1^2 a^2}{2^2} = \omega^2\mu(\epsilon_1-\epsilon_r)\frac{a^2}{2^2} \qquad (28)$$

$$\text{let} \quad q = h_0\frac{a}{2}, \quad p = k_1\frac{a}{2} \qquad (29)$$

$$-\frac{\epsilon_r}{\epsilon_1}p\cot p = q \qquad (30)$$

$$q^2+p^2 = \omega^2\mu(\epsilon_1-\epsilon_r)\frac{a^2}{4} = R^2 \qquad (31)$$

For Ku Band,

$a = .311'' \times 2.54 = 7.9\times10^{-1}$ cm $= 7.9 \times 10^{-3}$ m

$\omega = 2\pi f = 2\pi \times 15 \times 10^9 = 94 \times 10^9 = 9.4\times10^{10}$

$\epsilon_1 = 12 \times 8.854 \times 10^{-12} = 106 \times 10^{-12} = 1.06 \times 10^{-10}$

$\epsilon_r = 1 \times 8.854 \times 10^{-12} = 8.854 \times 10^{-12}$

$\mu = 1.257 \times 10^{-6}$

$(\epsilon_1 - \epsilon_r) = 11 \times 8.854 \times 10^{-12} = 97 \times 10^{-12} = 9.7 \times 10^{-11}$

$$R^2 = (9.4)^2 x10^{20} \times 1.257x10^{-6} \times 9.7x10^{-11} \times \frac{(7.9)^2 \times 10^{-6}}{4}$$

$$R = 9.4x10^{10} \times \sqrt{1.257} \times 10^{-3} \times \sqrt{97} \times 10^{-6} \times \frac{7.9x10^{-3}}{2} \qquad (32)$$

$$= 9.4 \times \sqrt{1.257} \times \sqrt{97} \times \frac{7.9}{2} \times 10^{10} \times 10^{-3} \times 10^{-6} \times 10^{-3}$$

$$= 9.4 \times 1.12 \times 9.9 \times 3.95 \times 10^{-2}$$

$$R = 4.4 \qquad (33)$$

$$R^2 = 19.3 \qquad (34)$$

A complete plot of 30 and 31 was run solving for p and q. The results are indicated in Figure 6.

From this

$$q = \frac{h_o a}{2} = 3.16 \qquad (35)$$

$$h_o = \frac{3.16 \times 2}{a} = \frac{6.32}{7.9 \times 10^{-3}} = 0.80 \times 10^3 \qquad (36)$$

$$e^{-h_o y} = e^{-1}$$

$$h_o y = 1$$

$$y = \frac{1}{0.8 \times 10^3} = 1.25 \times 10^{-3} \text{ m.} \qquad (37)$$

$$p = k_1 \frac{a}{2} \qquad k_1 = \frac{2p}{a} = \frac{3.06 \times 2}{a} = .78 \times 10^{3} \qquad (38)$$

$$\sin\left(k_1 \frac{a}{2}\right) = \sin 3.06$$

3.14 - 3.06 = .08 below π or above π,

$$\sin\left(k_1 \frac{a}{2}\right) = \sin .08 = .0799 .$$

Case II

$$H_x = \cos k_1 y \qquad (39)$$

$$h_0^2 + k_1^2 = \omega^2(\epsilon_1 - \epsilon_v) \qquad q = h_0 \frac{a}{2}$$

$$\frac{h_0^2 a^2}{2^2} + \frac{k_1^2 a^2}{2^2} = \omega^2 \mu(\epsilon_1 - \epsilon_v)\frac{a^2}{2^2} \qquad p = k_1 \frac{a}{2}$$

$$q^2 + p^2 = R^2 = (4.4)^2 \qquad (40)$$

$$\frac{\epsilon_v}{\epsilon_1} k_1 \tan\left(k_1 \frac{a}{2}\right) = h_0 \qquad (41)$$

$$\frac{\epsilon_v}{\epsilon_1}\left(k_1 \frac{a}{2}\right) \tan\left(k_1 \frac{a}{2}\right) = h_0 \frac{a}{2} \qquad (42)$$

$$\frac{1}{12} p \tan p = q \qquad (43)$$

$$\left(\frac{1}{12}\right)^2 p^2 \tan^2 p^2 = q^2$$

$$\frac{1}{144} p^2 \tan^2 p^2 + p^2 = (4.4)^2.$$

The roots for equations (40) and (43) are shown in Figure 8.

Case II a.

$$\begin{aligned} p &= 1.5396 \\ q &= 4.122 \end{aligned} \qquad (44)$$

$$C = e^{h_0 a/2} \cos\left(k_1 \frac{a}{2}\right) \qquad (45)$$

$$k_1 \frac{a}{2} = p \qquad\qquad h_0 \frac{a}{2} = q.$$

Solve for

$$h_0 = q\frac{2}{a} = \frac{4.122 \times 2}{7.9 \times 10^{-3}} = 1.04 \times 10^3 \ m^{-1} \qquad (46)$$

$$h_0 y = 1, \quad y \cong 10^{-3}$$

$$k_1 = p\frac{2}{a} = \frac{1.54 \times 2}{7.9 \times 10^{-3}} = .263 \times 10^3$$

$$\cos\left(k_1 \frac{a}{2}\right) = \cos p = \cos 1.5396 = .0308$$

i.e. near $\frac{\pi}{2}$. See Fig.(9)

Case II b.

$$p = 4.315, \quad q = .858$$

$$h_c = \frac{2q}{a} = \frac{1.7}{7.9} \times 10^3 = 2.15 \times 10^2$$

$$h_o y = 1, \quad y = \frac{1}{2.15} \times 10^{-2} = .465 \times 10^{-2} \qquad (47)$$

$$k_1 = \frac{2p}{a} = \frac{8.63}{7.9} \times 10^3 = 1.09 \times 10^3 \qquad (48)$$

$$\cos\left(k_1 \frac{a}{2}\right) = \cos p = \cos 4.315 = -.605$$

This tells us that in this mode, more of the field is external to the dielectric and hence there is a greater chance for loss.

EXPERIMENTAL DATA

A laboratory bench was set up with the components arranged as indicated in Figure 12. This is essentially a bridge arrangement with a klystron source capable of supplying Ku-band radiation, a bridge with an attenuator and phase shifter in one arm and sections of waveguide which can be removed in the other arm. A standard diode detector was used, the output of which was fed into an oscilloscope. The tuner is also indicated in the figure. The section of guide labelled "A" could be removed and four post conditions were studied as indicated in Figure 13. In Case A, the empty waveguide is filled with silicon 4-7/32" long with cross sectional area of .311 x 622", i.e., fitted into the inner dimensions of a Ku-band waveguide.

The following procedures were used particularly in the cases of Conditions B and C.

1. The attenuator was set at maximum, i.e., greater than 50 dB so that all of the power would flow through the arm containing the semiconductor.

2. The klystron frequency was changed slightly, at the same time adjusting the tuner on the detector for maximum power transfer. Usually three or four peaks were found which were indications that at these particu-

lar frequencies the semidonductor block was acting as a 1/2 wavelength transformer. It was found that these peaks were approximately .78 GHz apart. The data obtained is shown in Table II indicating the RF frequency at test, attenuation, and changes in attenuation over the control. From this table, it can be seen that the silicon filled waveguide gave an added attenuation of 4 dB, while the silicon waveguide with no cover gave an added attenuation of 5 dB. We conclude from this that one additional dB of attenuation was found by completely removing the metal cover from the silicon.

TABLE II

TRANSMISSION DATA

Condition	Frequency GH_z	Attenuation dB	Attenuation $A_{Control} - A_{Test}$ dB
Air filled (A) waveguide (control)	16.50	9.7 9.2 9.0 9.5 9.35 Average	0
Silicon filled (B) waveguide	15.40 15.46 16.18	13.0 13.0 13.5	4
Silicon waveguide $2\frac{1}{2}$" exposed (C) to air	15.54 16.40 17.16	14.1 13.9 14.7 14.5 14.6	5
Silicon removed $2\frac{1}{2}$" air space (D)	17.04	26.5	17

We should like to discuss the interpretation of the data in Table II.

1. The control test showed no resonance points under Condition A. There was no sign of 1/2 wavelength transformer action as might be expected.

2. Under Condition B, 1/2 wavelength transformer action was observed. The peaks in transmission are assumed to eliminate surface reflections and the 4 dB attentuation which was noted can be attributed entirely to the losses due to conductivity in the silicon.

3. Under Condition C, measurements were made at peak transmission values for the same reason the attenuation was found to be 5 dB indicating additional 1 dB loss. The exposed silicon was probed with metal structures such as a screwdriver or metal plate. Little or no effect on transmission was found by placing flat plates on the top of the silicon guide or on the sides of the silicon guide near its center of exposure. However, when placing a round metal rod approximately 1/8" diameter near the corner of the exit of the waveguide flange and the silicon on the upper flat piece, a slight change in balance was noted of approximately 0.2 to 0.3 dB. Changes from this preliminary probing appear to show that there may be some indication of power loss due to a poor fit between the silicon and the waveguide wall. This must be further examined and if so, there are still two approaches to overcome this problem. First a horn can be used to launch the wave. Second, antireflection coatings or grooves can be cut into the silicon section to obtain better matching from metal waveguide to silicon. In any case, we have demonstrated experimentally that there is very little, if any, electronic radiation emanating from the walls of the exposed silicon guide. This is a verification of the calculations which indicate only a very small fraction of power is located outside the semiconductor guide walls, and that indeed most of the power is being transmitted inside the semiconductor.

CONCLUSIONS

An analysis was made of waves in a dielectric slab. In considering this structure, it was expected that some insight would be obtained relating to the fraction of power propagating inside a dielectric waveguide.

The properties of the slab were chosen to match possible experiments with high resistivity silicon at frequencies associated with Ku band. That is, in the calculations chosen it was assumed that silicon has a dielectric constant of 12 and can be obtained lossless ($\sigma = 0$). The height of the dielectric slab was taken at the same dimensions as the inner height of metallic waveguide for Ku band (Figure 3 and 4), and a TM mode was calculated.

For the TM mode in the dielectric slab with materials and dimensions given it is seen that three possible modes can be maintained.

Mode 1, $H_x^o = \cos k_1 y$, $k_1 = .263\text{x}10^3$

Mode 2, $H_x^o = \sin k_1 y$, $k_1 = .78\text{x}10^3$

Mode 3, $H_x^o = \cos k_1 y$ or $k_1 = 1.09\text{x}10^3$

If we address ourselves to the question as to where most of the energy is located, we find that in all three cases, most of the power flows in the dielectric. This is a significant point, since if we want to construct active devices in the semiconductor dielectric, it is necessary for these devices to be in a location where they can interact with the energy being propagated.

In addition, we find that for the lower modes, the energy tends to be confined more tightly into the dielectric. This tendency appears as indicated in the following figures. (Figure 11).

The situation now appears hopeful for guiding the electromagnetic wave propagation in the semiconductor.

In the next phase of work we must analyze the mode characteristics for a rectangular waveguide[3]. We shall need this information in order to know best how to launch this wave from metal waveguide to semiconductor dielectric and vice versa with a minimum of losses or reflections. In addition, the coupling from the semiconductor guide to the devices will be of prime concern.

ACKNOWLEDGEMENT

Acknowledgements should be made to Dr. Felix Schwering and to Dr. Leonard Hatkin for their help during the course of this work, and to Mr. Heinz Wasshausen for the fabrication of silicon samples.

REFERENCES

1. Patent Disclosure: "New Quasi-Optics Concept for Miniaturization of Millimeter Wave Circuitry," Dr. H. Jacobs, 5 November 1970, Docket No. 19,940.

2. Jordan, E. C., and Balmain, K.G., "Electromagnetic Waves and Radiating Systems," Englewood Cliffs, N.J., Prentice Hall Inc., 1968, pp. 273-275.

3. Marcatili, E.A.J., "Dielectric Rectangular Waveguide and Directional Couplers for Integrated Optics," Bell System Technical Journal, Vol. 48, No. 7, Sep 69, pp. 2071-2103.

4. Goell, J. E., "A Circular-Harmonic Computer Analysis of Rectangular Dielectric Waveguides," Bell System Technical Journal, Vol. 48, No. 7, Sep 69, pp. 2133-2160.

GLOSSARY

f = frequency = 15.4 GHz

λ_{air} = wavelength in free space = 1.94 cm

λ_{si} = wavelength in silicon = .55 cm

λ_o = 2a = cutoff wavelength = 3.16 cm

η = free space impedance = 376 ohms

η_{si} = impedance in silicon = 107 ohms

σ = conductivity = 5.4×10^{-2} $(\Omega\, m)^{-1}$

α_{o2} = attenuation of silicon in guide = 2.89 neper/m

Z_{o1} = Z_{o3} = impedance in air filled waveguide =

$$\frac{376}{\sqrt{1-\left(\frac{\lambda_{air}}{\lambda_o}\right)^2}} = 476 \text{ ohm}$$

Z_{o2} = impedance in silicon filled guide

$$= \frac{\eta}{\sqrt{\epsilon}} \frac{1}{\sqrt{1-\left(\frac{\lambda_{si}}{\lambda_o}\right)^2}} = 107 \text{ ohms}$$

Γ_{o2} = propagation constant in silicon filled guide

$= \alpha_{o2} + j\beta_{o2}$

λ_{sig} = wavelength in silicon in guide

λ_g = wavelength in air filled guide

Block length = $\frac{10 \text{ cm}}{.558} \cong$ 18 wavelengths

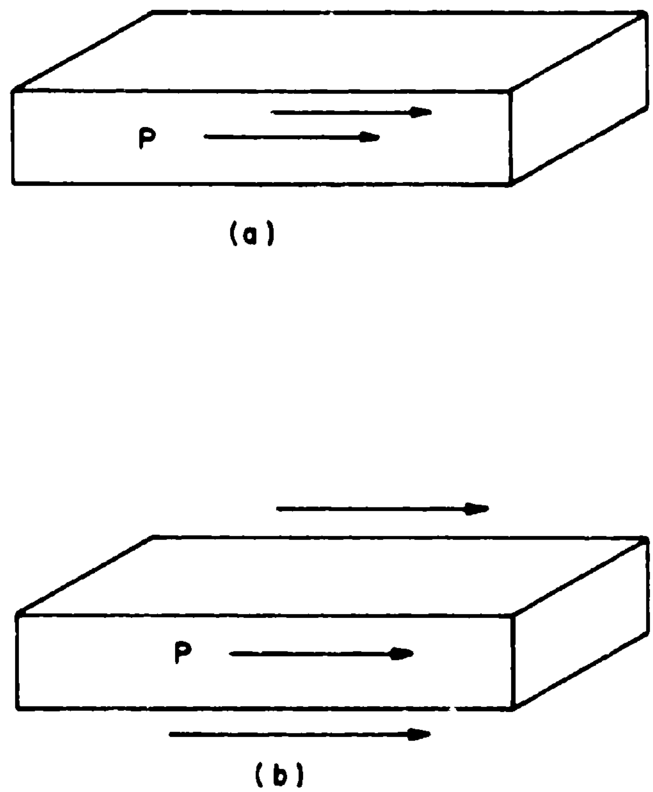

FIG. 1

POWER FLOW INTERNAL TO AND EXTERNAL TO DIELECTRIC

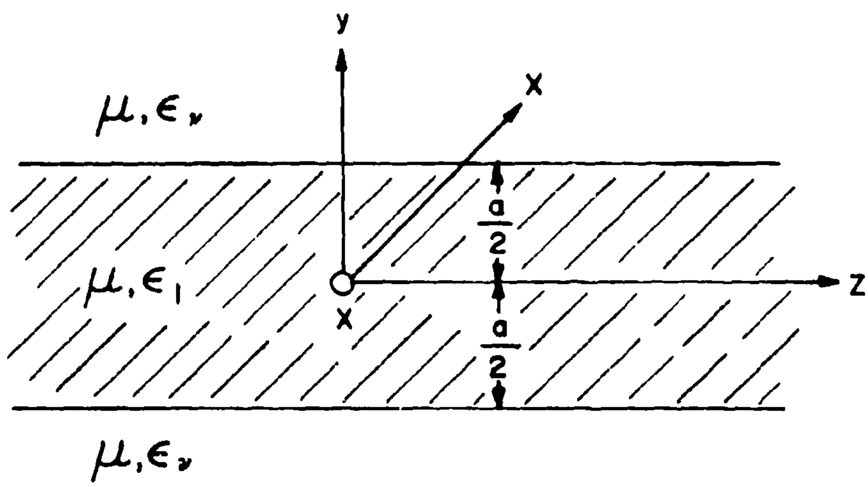

FIG. 2 DIELECTRIC SLAB WAVEGUIDE

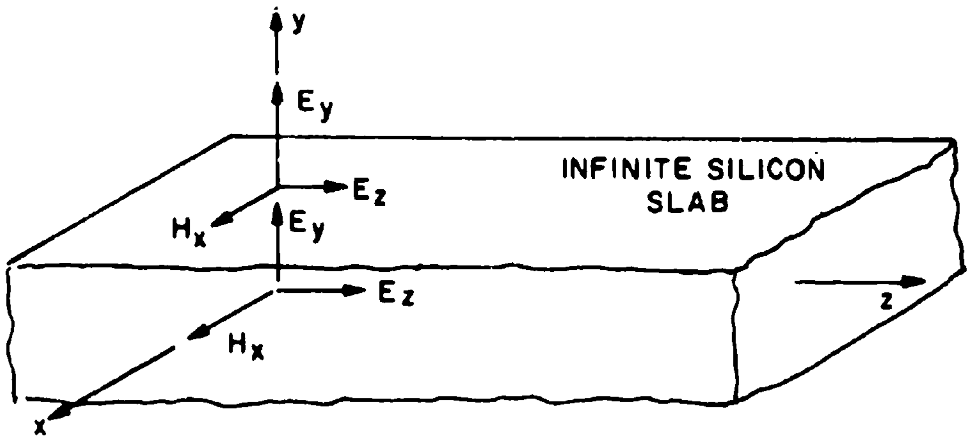

FIG.3 DIELECTRIC

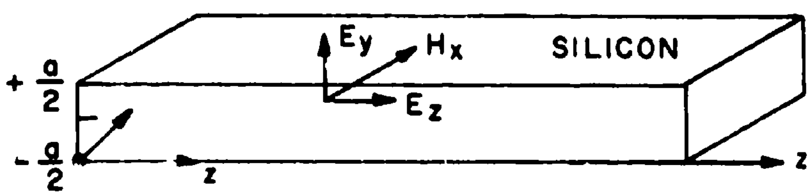

FIG. 4 DIELECTRIC

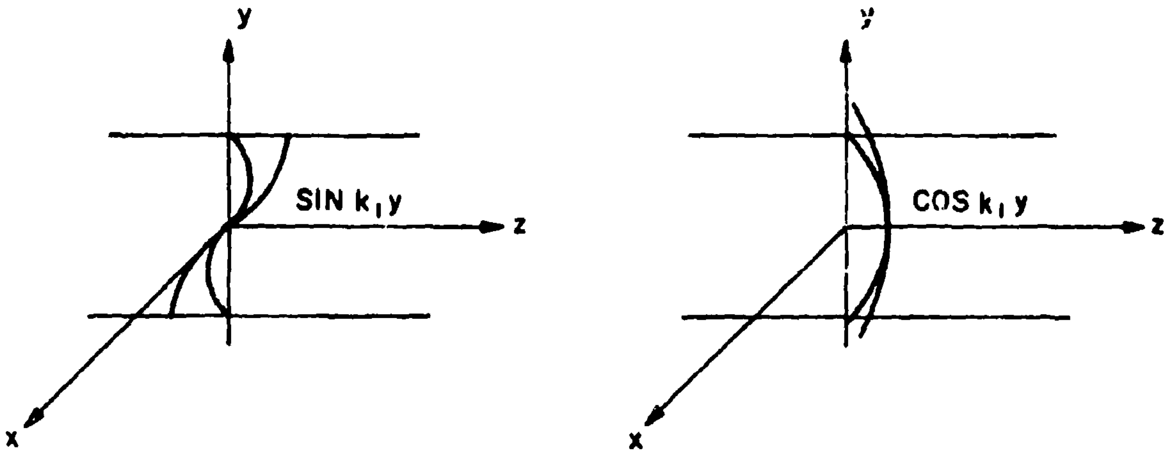

FIG. 5
POSSIBLE DISTRIBUTION OF FIELD IN DIELECTRIC

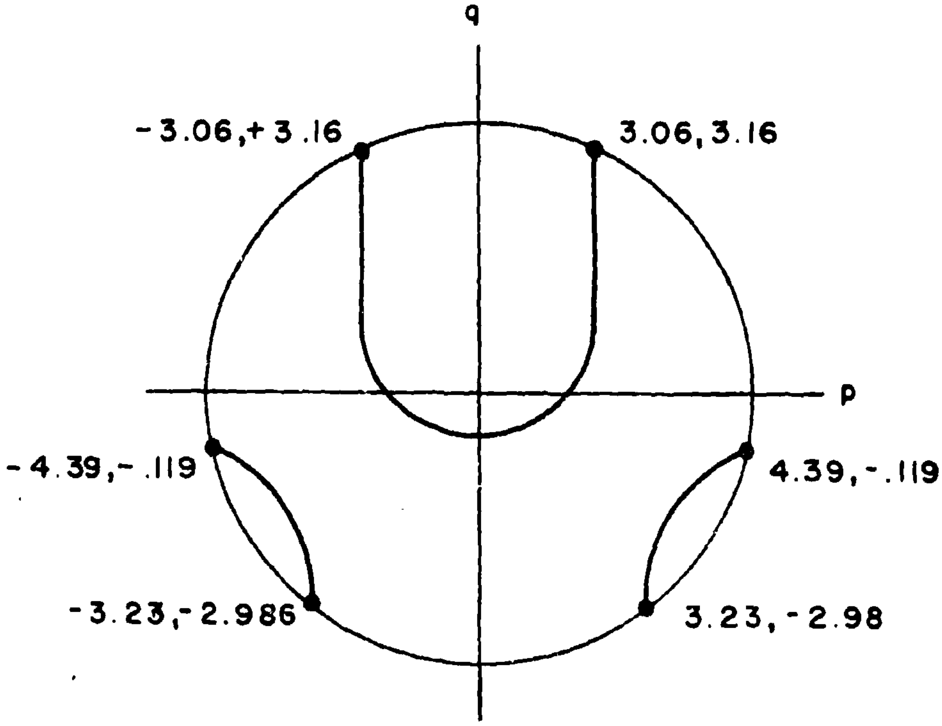

FIG. 6
GRAPHICAL METHODS OF SOLUTIONS

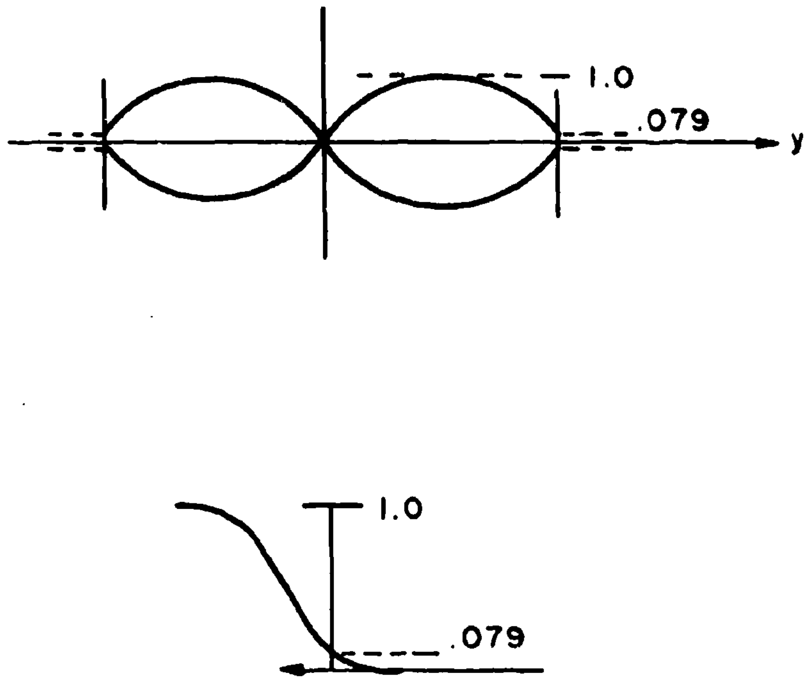

FIG.7

PENETRATION OF FIELD OUTSIDE SURFACE

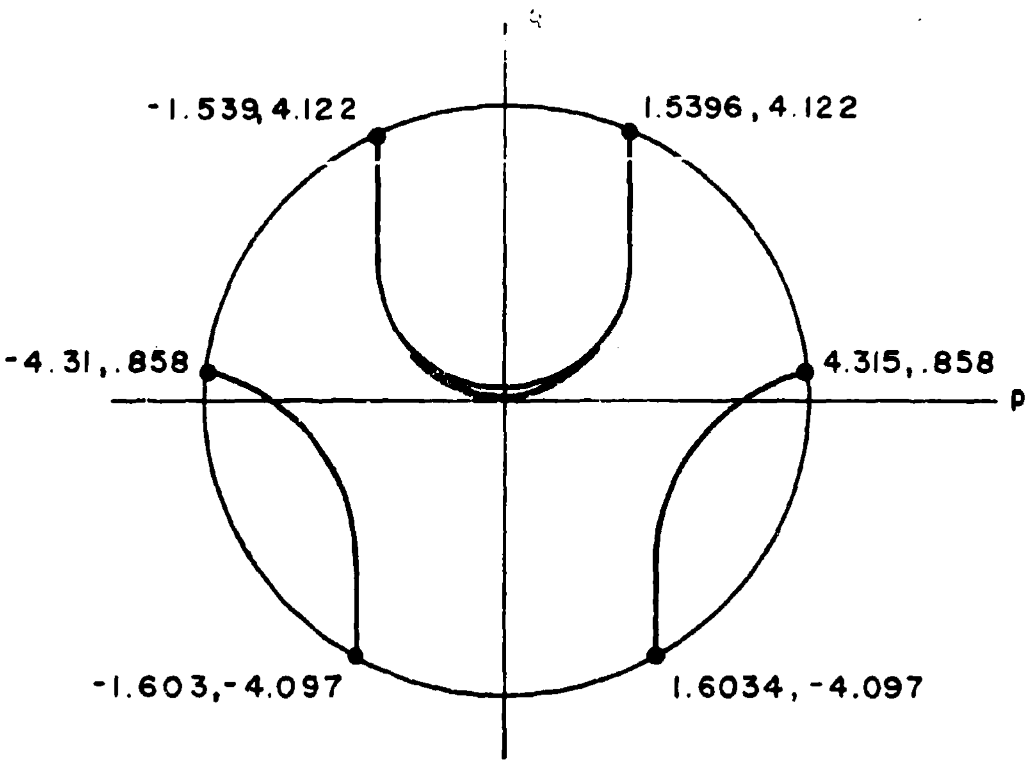

FIG. 8
GRAPHICAL SOLUTIONS

FIG. 9
COSINE MODE

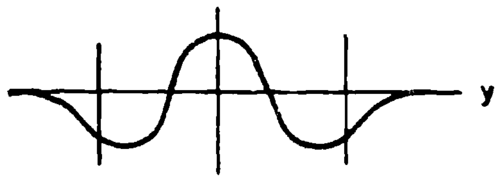

FIG. 10
SECOND COSINE MODE

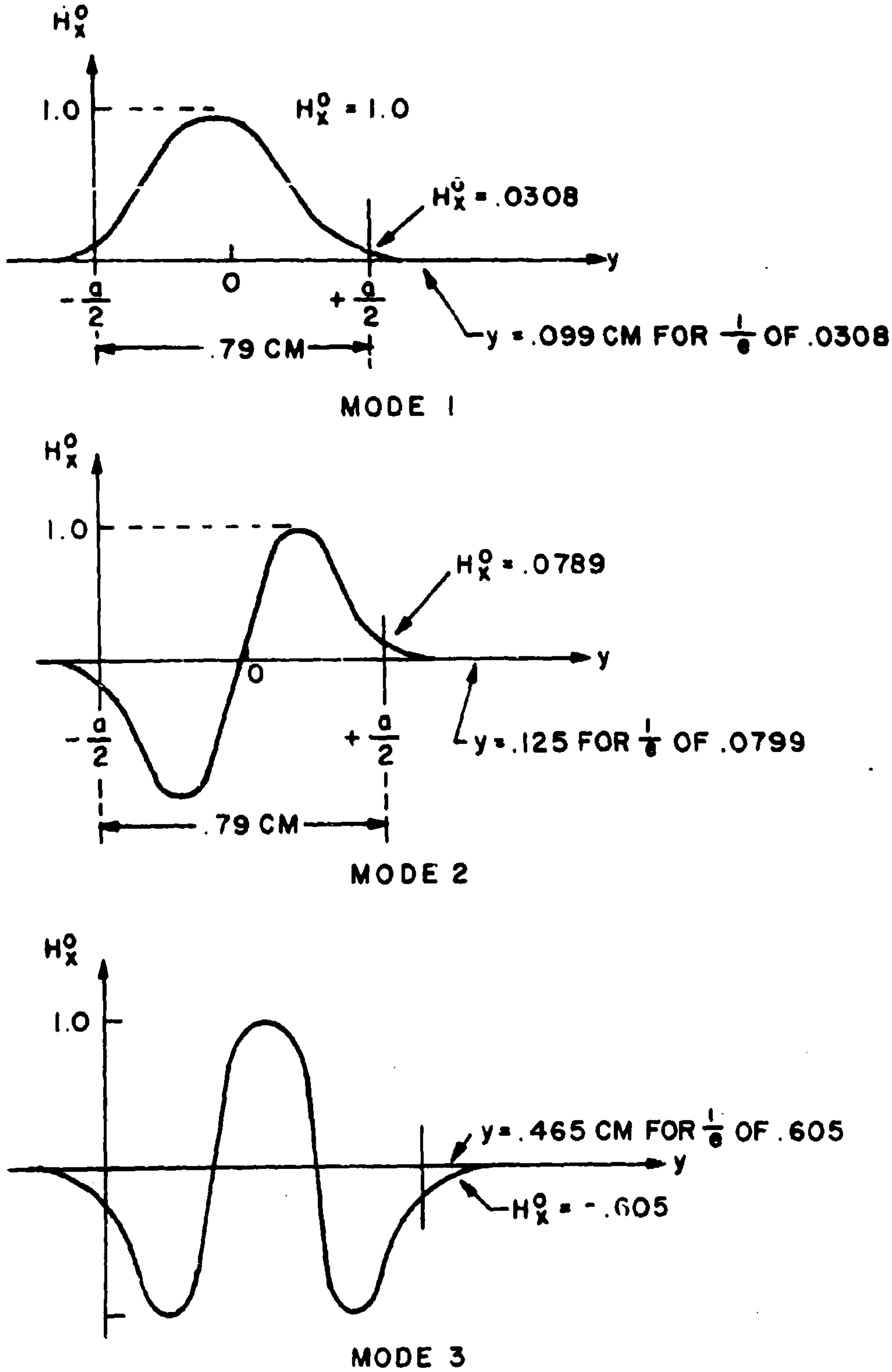

FIG. 11 FURTHER DETAILS ON POSSIBLE MODES

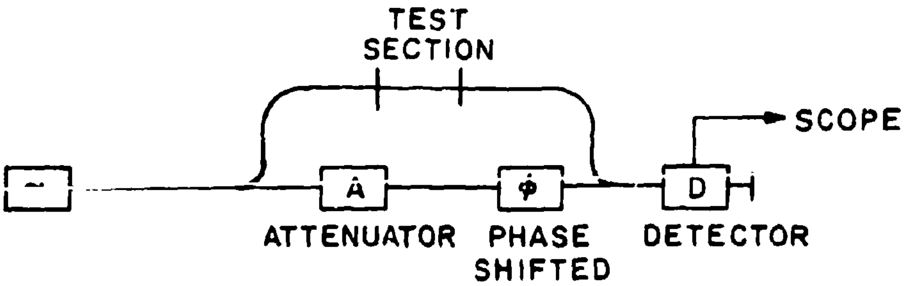

FIG. 12 EXPERIMENTAL BRIDGE CIRCUIT

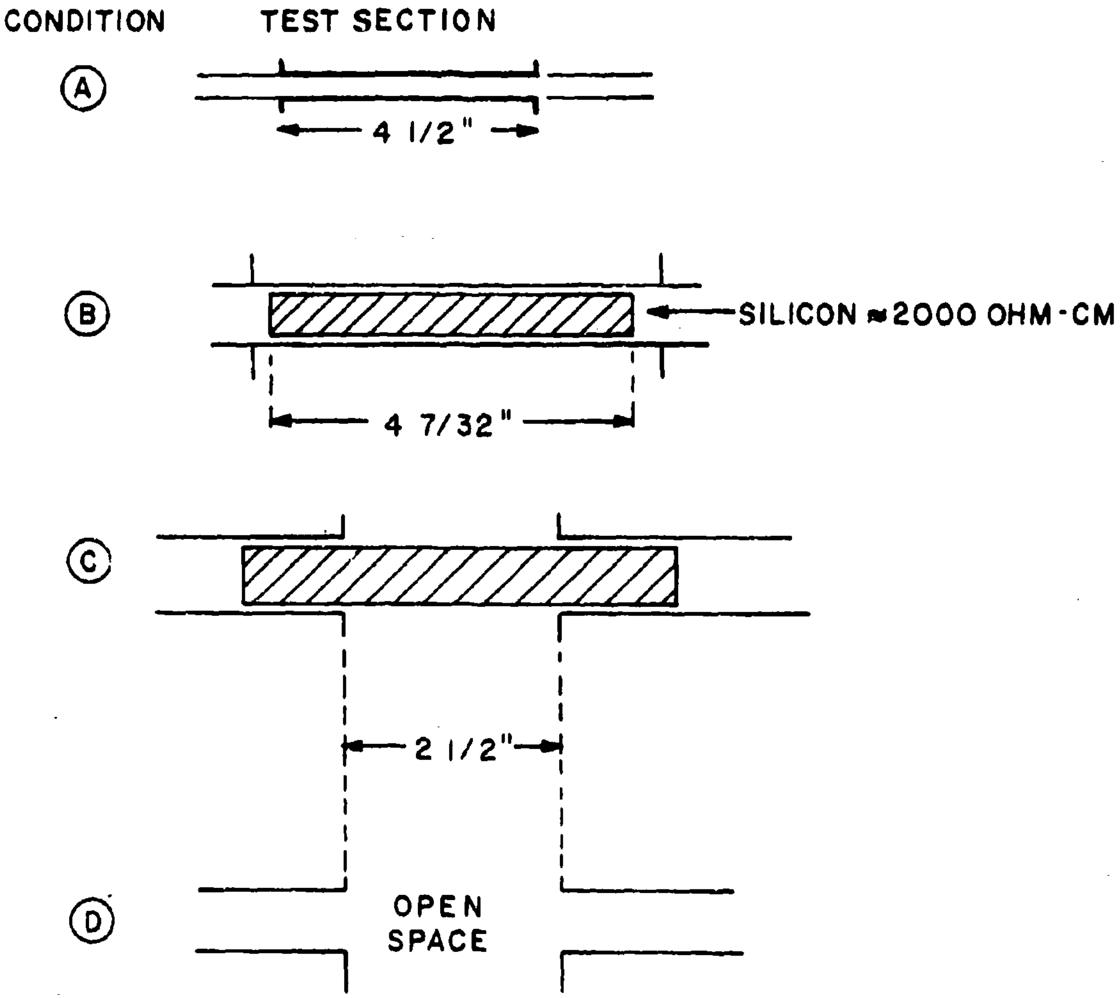

FIG. 13 EXPERIMENTAL ARRANGEMENTS

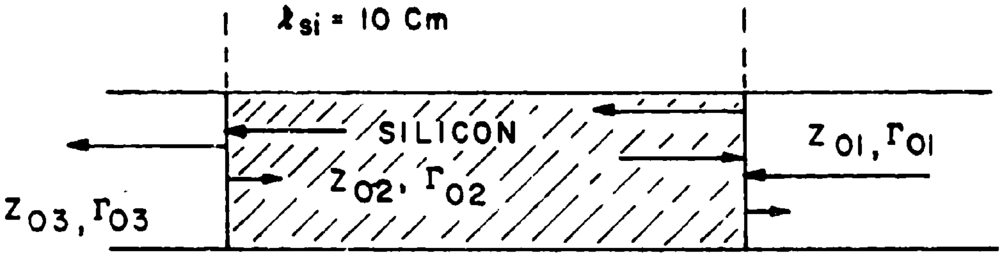

FIG. 14

MODEL FOR ANALYSIS OF MULTIPLE REFLECTIONS IN SILICON

APPENDIX A

Calculation of Attenuation Due to Silicon Block in the Experiment

The attenuation due to the conductivity and the multiple reflections within the semiconductor slab used in these experiments can be calculated from the ratio of the transmitted electric field to the incident electric field. This ratio is given by

$$\frac{E_o}{E_{in}} = \gamma_t\left(\cosh \Gamma_{o2} \ell - \frac{Z_{o2}}{Z_{ab}} \sinh \Gamma_{o2} \ell\right), \qquad (1)$$

where the transmission coefficient,

$$\gamma_t = \frac{2 Z_{ab}}{Z_{ab} + Z_{o1}} \qquad (2)$$

and Z_{o1}, the impedance of waveguide in air is

$$Z_{o1} = \frac{376}{\sqrt{1-\left(\frac{\lambda_{air}}{\lambda_o}\right)^2}}.$$

Z_{ab} the impedance at the first interface of the dielectrics is

$$Z_{ab} = Z_{o2}\left(\frac{Z_{o3} + Z_{o2}\tanh \Gamma_{o2} \ell}{Z_{o2} + Z_{o3}\tanh \Gamma_{o2} \ell}\right), \qquad (3)$$

as in Figure (14A) where $Z_{o3}\Gamma_{o3} = Z_{o1}\Gamma_{o1}$
and $\Gamma_{o2} = \alpha_{o2} + j\beta_{o2}$.

The impedance in the semiconductor is approximately

$$Z_{o2} = \frac{376}{\sqrt{\epsilon}}, \qquad \epsilon = 12.$$

Substituting into (3), $\Gamma_{o2} = \alpha_{o2} + j\beta_{o2}$

and the identities,

$$\tanh\ (x + y) = \frac{\tanh x + \tanh y}{1 + \tanh x \tanh y}$$

$$\tanh j\beta_{02} l = j \tan \beta_{02} l$$

equation (3) becomes

$$Z_{ab} = Z_{02}\left(\frac{Z_{03} + Z_{02} \tanh \alpha_{02} l}{Z_{02} + Z_{03} \tanh \alpha_{02} l}\right),$$

when $\beta_{02} l = n\pi$.

Substituting into (1) $\Gamma_{02} = \alpha_{02} + j\beta_{02} l$
and the identities,

$$\cosh (x+y) = \cosh x \cosh y + \sinh x \quad \sinh y$$

$$\sinh (x+y) = \sinh x \cosh y + \cosh x \ \sinh y$$

$$\sinh j\beta_{02} l = j \sin \beta_{02} l$$

equation (1) becomes

$$\frac{E_o}{E_{in}} = Y_t\left(\cosh \alpha_{02} l - \frac{Z_{02}}{Z_{ab}} \sinh \alpha_{02} l\right).$$

At 15.40 GHz (λ air = 1.94 cm) the 10 cm long silicon slab is a half wave transformer making $\beta_{02} l = n\pi$. The λ_0 cutoff wavelength for the metal guide is 3.16 cm, therefore

$$Z_{03} = Z_{01} = \frac{376}{\sqrt{1 - \left(\frac{\lambda_{air}}{\lambda_0}\right)^2}} = 476 \text{ ohms}$$

$$Z_{02} = \frac{376}{\sqrt{\epsilon_{Si}}} = 107 \text{ ohms}$$

$$\alpha_{02} l = \frac{Z_{02}\,\sigma_{Si}}{2} = 0.289 \text{ nepers for 10 cm length.}$$

$$\sigma_{Si} = 5.4 \times 10^{-2} \text{ ohm}^{-1} \text{ meter}^{-1}$$

Appendix A (Cont)

Inserting these values into equations (3) and (2) yields

$$Z_{ab} = 107\left(\frac{476 + 107 \tanh .289}{107 + 476 \tanh .289}\right) = 223 \text{ ohms}$$

and

$$\tau_t = \frac{2(223)}{223 + 476} = 0.64 .$$

Equation (1) then becomes,

$$\frac{E_o}{E_{in}} = .64\left(\cosh .289 - \frac{107}{223} \sinh .289\right) = 0.576$$

and the ratio of power transmitted is

$$\left|\frac{E_o}{E_{in}}\right|^2 = \left|.576\right|^2 = .331 \text{ or } 4.8 \text{ dB.}$$

The measured value of attenuation in silicon filled waveguide was approximately 4 dB. Considering the range of resistivities measured over the 10 cm long silicon slab, (1050 - 3300 ohm-cm) the average value used, (1830 ohm-cm) could be in error by approximately 20%. An agreement of calculated vs measured attenuation in this case is considered valid.

APPENDIX B

[illegible] for Roots of Equations 30 and 31

```
FILE:CSEQUA -04/21/71  4:02 PM.

100 BEGIN
200 $SA START1
300 "HENRY"
400 $SA START2
500 $ CARD
600 $$A COT
700 $ CARD
800 $SA FINDALLROOTS
900 $ CARD
1000 REAL PROCEDURE FCT(X); REAL X;
1100    FCT:=X*2\(1+COT(X)*2/144)-19.36;
1200 REAL ARRAY P, Q, CK[0:20];
1300 INTEGER K;
1400 FORMAT FMT1(X4, "P", X8, "Q", X8, "CK");
1500 FINDALLROOTS(FCT, -4.4, 4.4, 100, 9, P);
1600 FOR K:=1 STEP 1 UNTIL P[0]+.1 DO
1700    Q[K]:=-P[K]\COT(P[K])/12;
1800    CK[K]:=P[K]\P[K]+Q[K]\Q[K]-19.36;
1900 WRITE(TYPE, FMT1);
2000 FOR K:=1 STEP 1 UNTIL P[0]+.1 DO
2100    WRITE(TYPER, P[K], Q[K], CK[K]);
2200 $$A FINI
2300 END.

 END QUIKLST .8 SEC.

 RUNNING

TIME ON  1603         21 APR 1971



    P             Q            CK
-4.39839@+00-1.19029@-01 0.00000@+00
-3.23153@+00-2.98617@+00 0.00000@+00
-3.06126@+00 3.16068@+00 0.00000@+00
 3.06126@+00 3.16068@+00 0.00000@+00
 3.23153@+00-2.98617@+00 0.00000@+00
 4.39839@+00-1.19029@-01 0.00000@+00
TIME OFF      1603

 END CSEQUA 2.0 SEC.
```

```
FILE:CSEQUA -04/22/71 10:35 AM.

BEGIN
$$A START1
"HENRY"
$$A START2
$ CARD
$$A TAN
$ CARD
$$A FINDALLROOTS
$ CARD
REAL PROCEDURE FCT(X); REAL X;
    FCT:=X*2\(1+TAN(X)*2/144)-19.36;
REAL ARRAY P, Q, CK[0:20];
 REAL P1, Q1;
INTEGER K;
FORMAT FMT1(X4, "P", X8, "Q", X8, "CK");
FINDALLROOTS(FCT, -4.4, 4.4, 100, 9, P);
FOR K:=1 STEP 1 UNTIL P[0]+.1 DO
    Q[K]:=P[K]\TAN(P[K])/12;
    CK[K]:=P[K]\P[K]+Q[K]\Q[K]-19.36;
WRITE(TYPE, FMT1);
FOR K:=1 STEP 1 UNTIL P[0]+.1 DO
    WRITE(TYPER, P[K], Q[K], CK[K]);
 WRITE(TYPER);
 FOR P1:=-4.4 STEP .1 UNTIL 4.41 DO
   BEGIN
     Q1:=P1\TAN(P1)/12;
     WRITE(TYPER, P1, Q1);
   END;
$$A FINI
END.

END QUIKLST 1.3 SEC.

COMPILING.

END COMPILE 9.7 SEC.

RUNNING

TIME ON  1036        22 APR 1971
```

P	C	CK
-4.31552@+00	8.58076@-01	0.00000@+00
-1.60339@+00	-4.09745@+00	0.00000@+00
-1.53968@+00	4.12182@+00	0.00000@+00
1.53968@+00	4.12182@+00	0.00000@+00
1.60339@+00	-4.09745@+00	0.00000@+00
4.31552@+00	8.58076@-01	0.00000@+00

-4.40000@+00	1.13532@+00
-4.30000@+00	8.19095@-01
-4.20000@+00	6.22223@-01
-4.10000@+00	4.86372@-01
-4.00000@+00	3.85940@-01
-3.90000@+00	3.07913@-01
-3.80000@+00	2.44959@-01
-3.70000@+00	1.92626@-01
-3.60000@+00	1.48040@-01
-3.50000@+00	1.09254@-01
-3.40000@+00	7.48898@-02
-3.30000@+00	4.39301@-02
-3.20000@+00	1.55930@-02
-3.10000@+00	-1.07510@-02
-3.00000@+00	-3.56366@-02
-2.90000@+00	-5.95480@-02
-2.80000@+00	-8.29570@-02
-2.70000@+00	-1.06364@-01
-2.60000@+00	-1.30346@-01
-2.50000@+00	-1.55630@-01
-2.40000@+00	-1.83203@-01
-2.30000@+00	-2.14516@-01
-2.20000@+00	-2.51868@-01
-2.10000@+00	-2.99223@-01
-2.00000@+00	-3.64173@-01
-1.90000@+00	-4.63457@-01
-1.80000@+00	-6.42939@-01
-1.70000@+00	-1.09035@+00
-1.60000@+00	-4.56434@+00
-1.50000@+00	1.76268@+00
-1.40000@+00	6.76420@-01
-1.30000@+00	3.90228@-01
-1.20000@+00	2.57215@-01
-1.10000@+00	1.80103@-01
-1.00000@+00	1.29784@-01
-9.00000@-01	9.45119@-02
-8.00000@-01	6.86426@-02
-7.00000@-01	4.91335@-02
-6.00000@-01	3.42068@-02
-5.00000@-01	2.27626@-02
-4.00000@-01	1.40931@-02
-3.00000@-01	7.73341@-03
-2.00000@-01	3.37850@-03
-1.00000@-01	8.36122@-04

```
2.00998@-10 3.36669@-21
1.00000@-01 8.36122@-04
2.00000@-01 3.37850@-03
3.00000@-01 7.73341@-03
4.00000@-01 1.40931@-02
5.00000@-01 2.27626@-02
6.00000@-01 3.42068@-02
7.00000@-01 4.91335@-02
8.00000@-01 6.86426@-02
9.00000@-01 9.45119@-02
1.00000@+00 1.29784@-01
1.10000@+00 1.80103@-01
1.20000@+00 2.57215@-01
1.30000@+00 3.90228@-01
1.40000@+00 6.76420@-01
1.50000@+00 1.76268@+00
1.60000@+00-4.56434@+00
1.70000@+00-1.09035@+00
1.80000@+00-6.42939@-01
1.90000@+00-4.63457@-01
2.00000@+00-3.64173@-01
2.10000@+00-2.99223@-01
2.20000@+00-2.51868@-01
2.30000@+00-2.14516@-01
2.40000@+00-1.83203@-01
2.50000@+00-1.55630@-01
2.60000@+00-1.30346@-01
2.70000@+00-1.06364@-01
2.80000@+00-8.29570@-02
2.90000@+00-5.95480@-02
3.00000@+00-3.56366@-02
3.10000@+00-1.07510@-02
3.20000@+00 1.55930@-02
3.30000@+00 4.39301@-02
3.40000@+00 7.48898@-02
3.50000@+00 1.09254@-01
3.60000@+00 1.48040@-01
3.70000@+00 1.92626@-01
3.80000@+00 2.44959@-01
3.90000@+00 3.07913@-01
4.00000@+00 3.85940@-01
4.10000@+00 4.86372@-01
4.20000@+00 6.22223@-01
4.30000@+00 8.19095@-01
4.40000@+00 1.13532@+00

TIME OFF     1037

END CSEQUA 3.7 SEC.
```